

1 The use of Ground–Probing Radar within a digital environment on archaeological sites

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1.1 INTRODUCTION

Ground–Probing Radar (GPR) has been used in archaeology for a number of years with varying degrees of success. The latter has largely been dependent on subsurface conditions, the sophistication of field and processing techniques available at that time and, to a degree, the technical expertise of the operator of the equipment. The potential for the technique, particularly in urban environments which are not accessible to more conventional remote sensing techniques, has been apparent from the outset, but it is only now — through increased processing power, both in the field and in the laboratory that GPR is beginning to fulfil, expectations on any sort of consistent basis.

The following discussion involves advances made in GPR data processing and interpretation using a number of sites in the centre of Gloucester, England as a test bed. Gloucester is a particularly valuable model as it has a deep (up to 6 m) and complex stratigraphy, containing evidence for a Roman fortress and *colonia*, Saxon town and medieval city and Civil War siegeworks. The core of the city within the circuit of the Roman walls covers *c* 17ha (43 acres) and is now almost entirely covered by standing buildings, most having cellars, or areas of demolished buildings (also cellared) that are now covered with concrete or tarmac surfaces. The sub–surface also varies from sands to Lias clays, with some sites having a high degree of water logging. Despite the long history of archaeological activities in the city going back over 100 years, there are still vast gaps in our knowledge of the internal layout of the settlement. This makes it very difficult to offer prospective developers and the planning authority an accurate forecast of the archaeological implica-

tions of any proposed development scheme. GPR was therefore seen as being of enormous potential in allowing the evaluation of sites with the minimum disruption to the current economic usage. The first GPR surveys were carried out here in 1989 with as much mediocre success as elsewhere. It has only been since 1991, using the systems outlined in this paper, that results of consistent quality have been obtained.

In 1991 an extensive GPR survey was commissioned in the Blackfriars area of central Gloucester, covering *c* 2100 m² on the site of the Lady-bellegate Street car park (Figure 1.1). This was in a position of potentially high sensitivity — at the heart of the Roman fortress and with the prospect of substantial Roman town houses, Saxon occupation and then ancillary buildings to the medieval friary of the Blackfriars. A medieval cemetery attached to the friary was also suspected to be in this general area although its exact position was unknown. The quality of possible archaeology was such that dealing with it — either by preservation or by excavation — was likely to be extremely expensive, but the bulk of the site was inaccessible for conventional evaluation (being an operating car park). GPR was therefore seen as a cost–effective way of carrying out a broad evaluation on a more extensive scale than conventional trial trenching on a restricted scale would allow (Figure 1.2). Subsequently, a survey was commissioned along one of Gloucester’s main streets (Westgate Street) to locate both modern services and archaeological features prior to designing a pedestrianisation scheme. This was known to have once had a range of medieval buildings, including two churches and a market building along it — the exact location and plan of which has been lost.



Figure 1.1: View across the Ladybellegate Street Car Park, Gloucester towards Blackfriars and the trial trench excavated in the Summer of 1991. This was dug to calibrate a GPR survey carried out over the 2100 m² of the car park which was otherwise inaccessible to conventional forms of archaeological evaluation. The GPR survey itself was carried out overnight to avoid disturbance to the car park operations. (photo: City Archaeology Unit, Gloucester City Council)



Figure 1.2: Excavation in progress on the levels of the medieval cemetery. Around 140 burials in all were discovered within the 20 m long trench, with the GPR survey suggesting that the total area of the cemetery might include c 2000. (photo: City Archaeology Unit, Gloucester City Council)

1.2 GROUND PROBING RADAR

1.2.1 The geophysical principle

This is not the place for a full discussion of the geophysical theory behind GPR, although it will be argued that a knowledge of these principles is essential if accurate interpretations of the results is to be obtained. Basically, GPR is a geophysical technique where electromagnetic impulses are fired into the ground and reflections from underground surfaces and objects are recorded. The standard operating technique of GPR within archaeological projects uses a transmitter and receiver co-located on the ground surface. The transmitter transmits impulses into the ground at a constant rate whilst the transmitter/receiver pair is pulled across the ground, thus producing a time cross-section of the subsurface below the traverse. Another operating technique which can be used in conjunction with the former is called the Wide Angle Reflection and Refraction method (WARR). In this case, the transmitter is left stationary on the surface and the receiver moved away at a constant speed. The resultant data can be analysed to give a velocity profile of the subsurface — this together with the time-section can be integrated to produce an accurate depth-section.

1.2.2 Interpreting the results

2.2.1 Current Problems

The end-user of GPR normally sees the results as miles and miles (or kilometres and kilometres to be in the spirit of 1992) of black and white or multi-colour time/depth sections. Quite often the end-user might only be given traces and plans with a number of possible anomalies marked for him/her to make an assessment of what their archaeological character and significance might be. In simple recording terms, a wall and a robber trench may give much the same reading but their archaeological significance could be very different. Archaeologists have to be aware of this problem inherent in the system — Geophysicists are not Archaeologists and vice versa. A way has to be found to bring the two fields together in order to use GPR effectively in an archaeological environment (for further discussion of this see Atkin & Milligan 1992).

The black and white charts can be produced in the field and have been the traditional tool used to make interpretations of the GPR data, but the resolution of these charts are poor and a lot of valuable information can be masked. Multi-colour charts show the same information but instead of grey scales the signal amplitude is mapped to 16 individual colours in a digital environment.

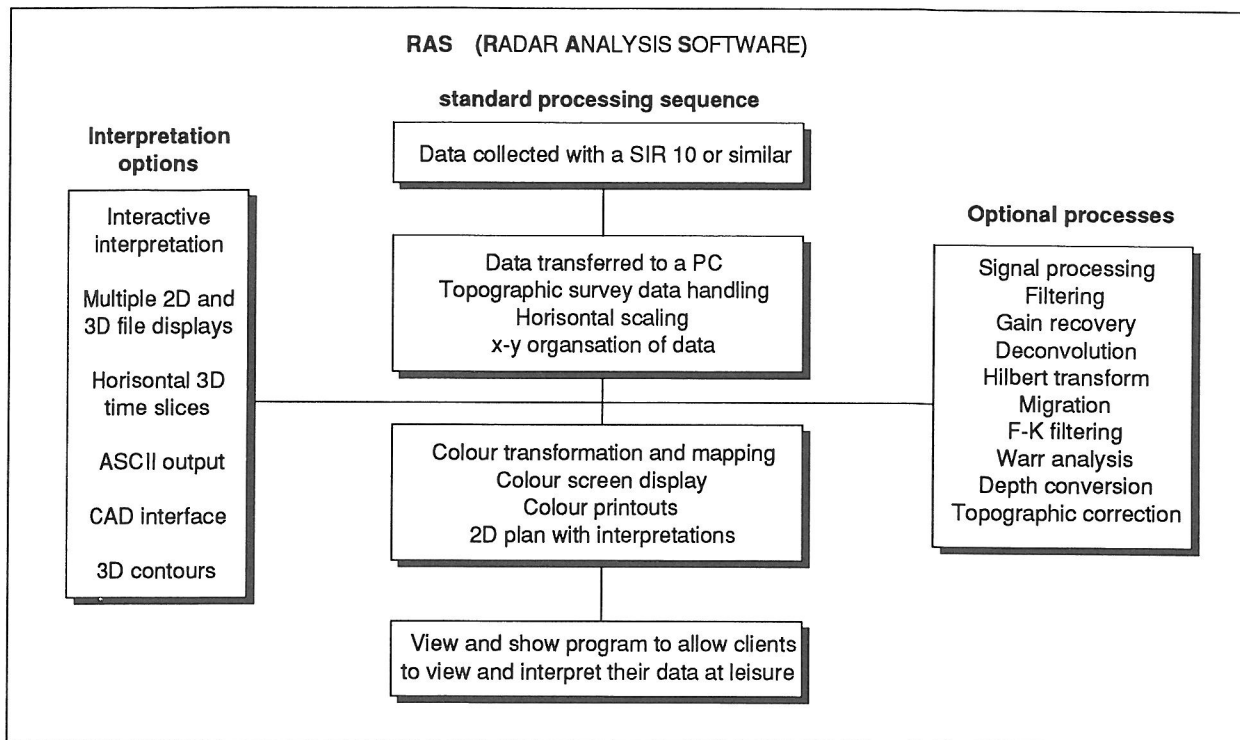


Figure 1.3: Chart showing the features of the RAS software. Please note that the major part of the development concentrated on Interpretation and is shown on the left side of the flow diagram.

This processing is termed “digital processing”, but often all that has been carried out in the digital domain is colour mapping and printing. The result of this might be no better than the original black and white charts and can lead to misinterpretations by reading great significance to each individual colour band. It is easy to forget that the data is a complex interference pattern of waveform data and to try to look at this in terms of an image, as in traditional remote sensing and photogrammetry or in the drawing up of a standard archaeological section. This is probably the major cause of disappointing GPR surveys in archaeology, certainly in the UK. Care has also to be taken in choosing colour palettes — pretty pictures can be the most hard to interpret!

1.2.2.2 Improving the results

In trying to improve the system there were three particular technical problems that had to be overcome:

- 1) Large data storage requirement;
- 2) Excessive amounts of chart paper;
- 3) Poor visualisation of subsurface features from the vast amount of data collected during a GPR survey.

It had been thought that the major problem in carrying out digital data processing was the size of data storage media that was required to store the data, with a GPR survey perhaps producing gigabytes of data. This is not true, and typically in one day on an archaeological site 1 km of line data would be collected yielding around 26 Mbyte (this can be reduced to 13 Mbyte by halving the sample rate without interfering with the integrity of the data). These figures mean that currently available low cost storage is adequate. If vast amounts of data storage is required it is likely that the data has been very over-sampled.

There were more serious problems with the commercial processing software currently available to process this data. This software concentrated on applying “seismic” processes to radar data which may, or may not, be applicable to the GPR data collected on-site. Also no extensive line by line batch processing was available — which is essential when dealing with large volumes of data. As a result, interpretation has largely been a manual process — comparing charts laid out on the floor or wall.

1.3 RAS — RADAR ANALYSIS SOFTWARE

1.3.1 Digital processing techniques

In order to overcome the problems encountered on the sites at Gloucester, which may well be typical for urban archaeological sites, new software was developed as from 1991. This software has now come to be known as RAS (Radar Analysis Software) and the structure of which is shown on Figure 3. As a result, when combined with using the digital hardware system of *SIR 10* (by GSSI), the technique is now able to recover up to 200% more interpretable data from the ground than was possible in 1989.

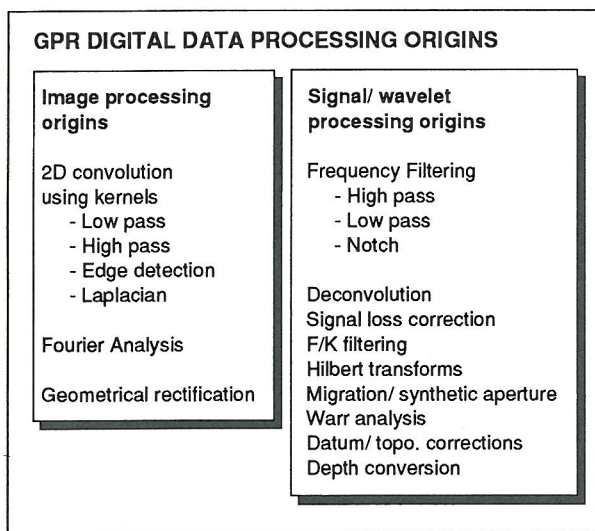


Figure 1.4: GPR processing comes from two sources — Signal/Wavelet Processing (Seismics) and Image Processing (Remote Sensing). The relevant processes are shown above.

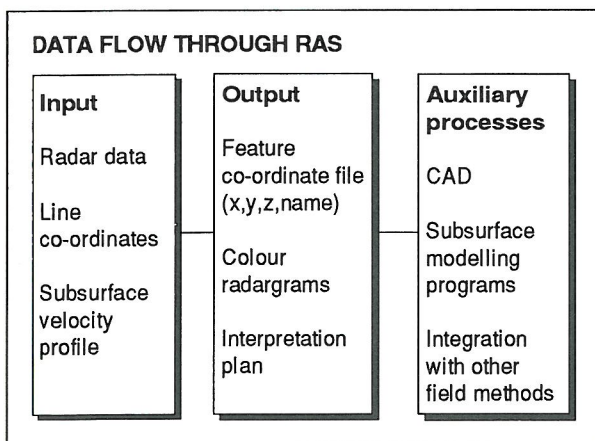


Figure 1.5: Figure showing the data requirements for processing through RAS. Note an important step is to combine the survey positions with the collected radar data.

The way in which the data is digitally handled and presented on the screen rather than relying on paper traces was the major innovative features of RAS and primarily it was designed as an interpretation tool. Digital data processing techniques in GPR have been largely borrowed from two sources:

- 1) *Large-Scale Seismics (Oil Industry)*: involving Signal/Wavelet processing;
- 2) *Remote Sensing*: involving image processing.

The methods are shown on Figure 1.4.

Image processing can be used to improve resolution but is less predictable in a signal processing sense than frequency filtering and can have the added drawback of introducing large sidelobes to the data. The aim of processing is to change the irregularly-shaped impulse from the antenna to a single, sharp, impulse. Sidelobes are when extra lobes are added to the impulse by poor filtering. Good filters will not introduce significant sidelobes. At all times the processor and interpreter of the data has to bear in mind that the radargram represents a complex interference pattern and not a 2D image as in remote sensing. Every process applied to the data should be geophysically and scientifically justified with respect to a wave travelling through the ground. The correct handling of the data avoids unwanted processing artefacts causing misinterpretations of the data. As in all walks of life, a relevantly qualified and experienced person should be in charge of the operations. GPR is not a technique that can be used simply by buying a system off the shelf.

The following gives an indication of where each processing technique should be employed:

- *Signal/ Wavelet Processing*: Signal analysis and processing to improve horizontal and vertical resolution; Depth conversion and Datum correction;
- *Image processing*: Filtering to tidy the data generally before final presentation; Image enhancement of horizontal time slice data (to be discussed later) and sub-surface layer data.

The GPR signal data gathered in the field is collected in a grid of parallel transects and has to be merged on the computer with the survey information (XY co-ordinates of the grid) in order that it is possible to “pick” features on the computer screen and record the information as X,Y and Z co-ordinates. This forms the basic front-end of the RAS software. Figure 1.5 shows the data flow through RAS.

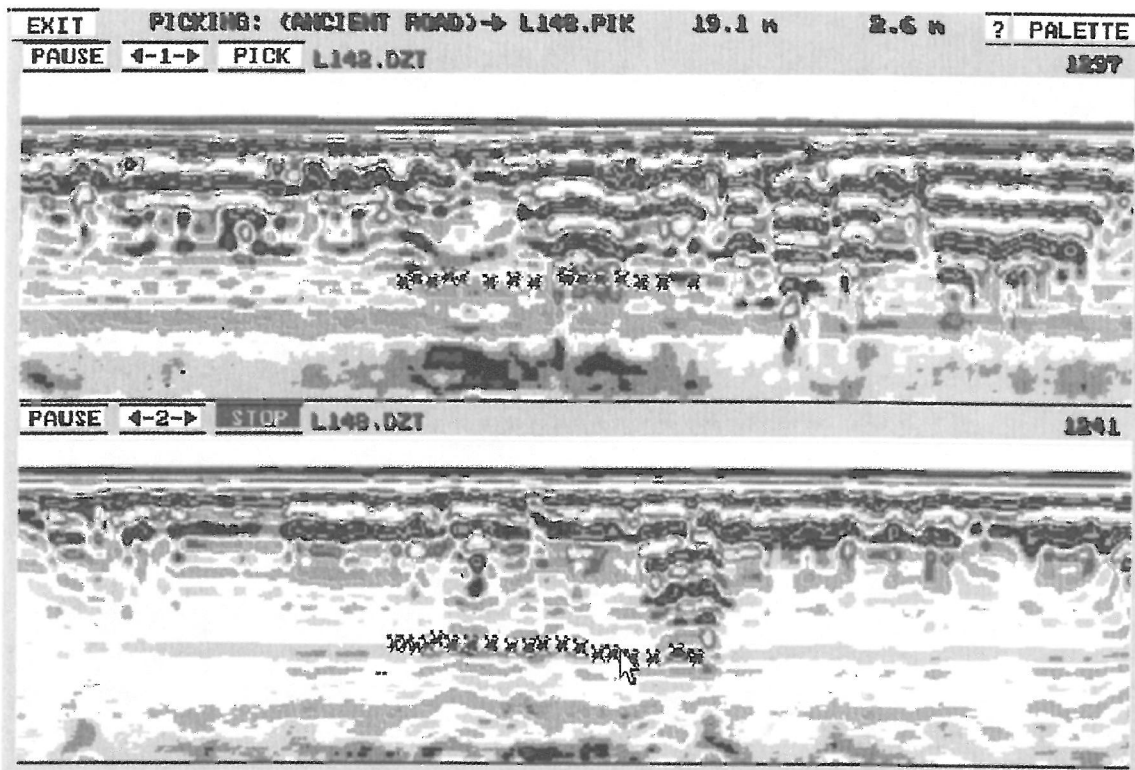


Figure 1.6: 2D display showing a section through a Roman road on the Ladybellegate Street, Gloucester site. Multiple file displays allow comparing of parallel transects and has been found to help establish correlations within a survey area.

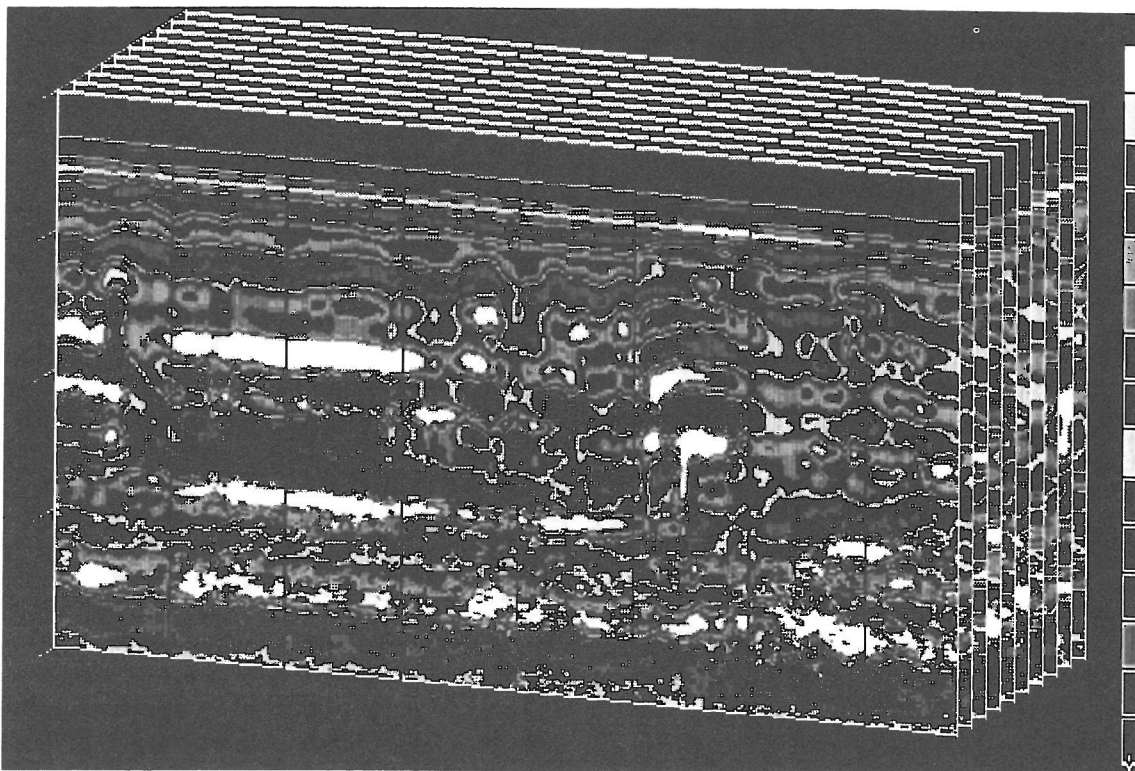


Figure 1.7: 3D display of ten parallel vertical slices. Each individual slice can be taken away or added interactively to allow the establishment of correlations from line to line. This system has been found to be useful for tracking walls/foundations, roads and ditches i.e. linear archaeological features.

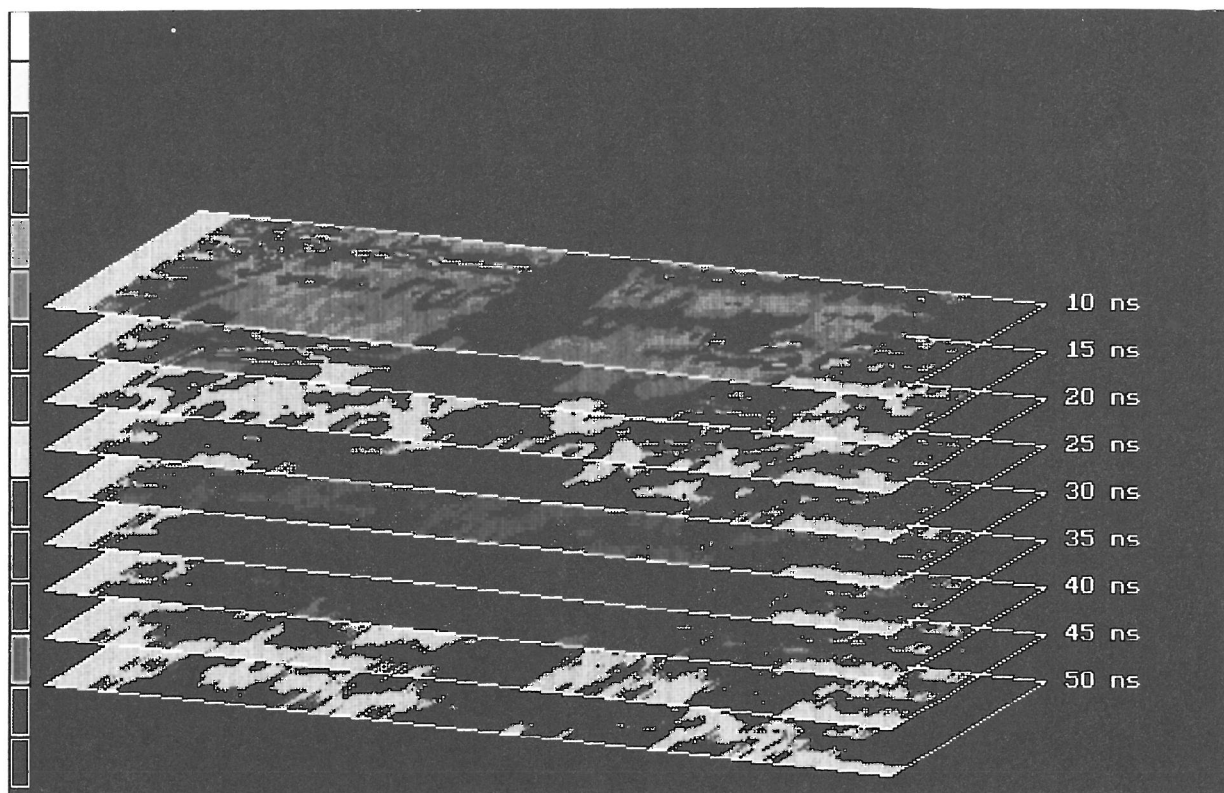


Figure 1.8: 3D display of 10 horizontal slices. These slices have been extracted from the 3D data set and represent slices at constant time delays in the data. They could be thought of as depth slices if the sub-surface is assumed to be laterally homogeneous in terms of electro-magnetic properties. This particular example shows the "King's Board" on Westgate Street, Gloucester as a curved feature on the right of the upper slice.

1.3.1.1 Vertical slicing

An important step in the interpretation of the processed GPR data is the ability to compare visually parallel lines and two features were developed to allow this.

- 1) It is now possible to display up to 4 parallel lines on the screen at one time and pick and categorise features (Figure 1.6). Features are then plotted on a map on the computer screen (or printer) showing the line to line correlation's;
- 2) The RAS 3D vertical slice display (Figure 1.7) shows up to 10 parallel lines in a display similar to a pack of cards. Interactively the user can flick between the lines looking correlations from line to line. These techniques have been used to track linear features within the Gloucester datasets — walls, ditches, foundations, roads and modern services.

1.3.1.2 Horizontal slicing

Another important part of the 3D software is the horizontal time slice displays (Figure 1.8). These are formed by extracting data from up to 10 par-

allel lines at equal depths in the time sections, equivalent to taking horizontal slices from the 3D vertical slice display. A problem with these displays is that the data is well-sampled *along* the lines but poorly-sampled *between* the lines. This means that if a plan plot of a horizontal time slice was shown, stripes at right angles to the line directions would appear in the data due to excessive interpolation. Various "intelligent" interpolation algorithms have been tested but none have been found to be of any benefit. To overcome this interpolation problem, the horizontal time slices are displayed at an angle showing 3D perspective and only 3 new points therefore need to be interpolated between samples. Initial results have been promising and have paid a valuable role in interpretation of archaeological GPR data.

On the Ladybellegate Street site it was possible to pick up the trends of the walls of two 2nd — 4th century town houses with linear zones in between as the line of the Roman roads. On the subsequent Westgate Street survey in Gloucester, it was possible to establish the plan of the medieval Kings Board (Cheese Market). The vertical slices revealed two stages of demolition (with an

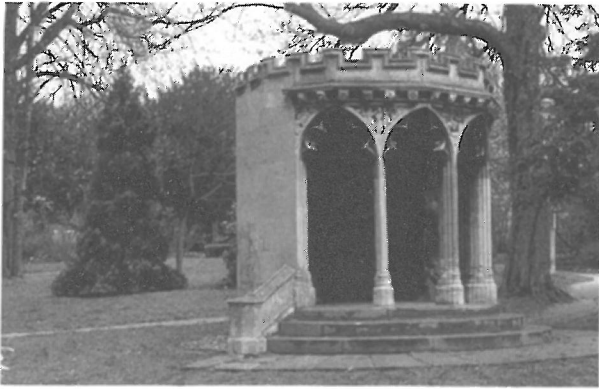


Figure 1.9: The "King's Board", Gloucester. This is the only surviving part of the medieval mint and later cheese market which was built down the centre of Westgate Street, Gloucester. It now stands in a suburban park and its original context has been the subject of much local debate. The actual site of the Kings Board is now inaccessible but a GPR survey carried out in advance of a pedestrianisation scheme across its location did, indeed, reveal a semi-circular feature on the north side of a long rectangular building. This has raised the suggestion that the surviving feature was a pulpit facing onto an open market square in front of the building. (photo: City Archaeology Unit, Gloucester City Council)

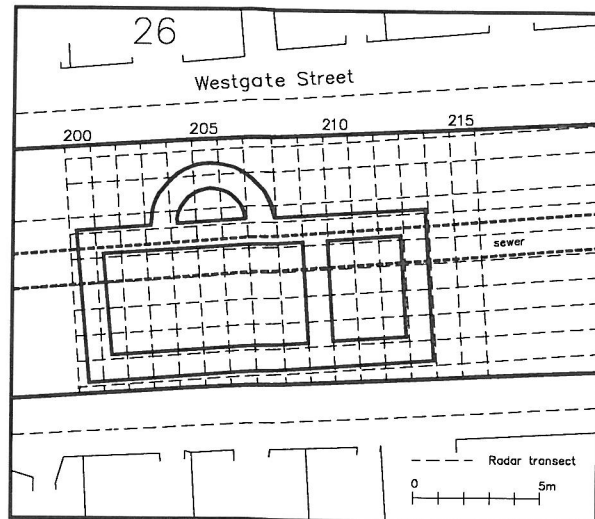


Figure 1.10: Plan of "King's Board", Gloucester, based on the results of the GPR survey and observation of a sewer trench cut through it.

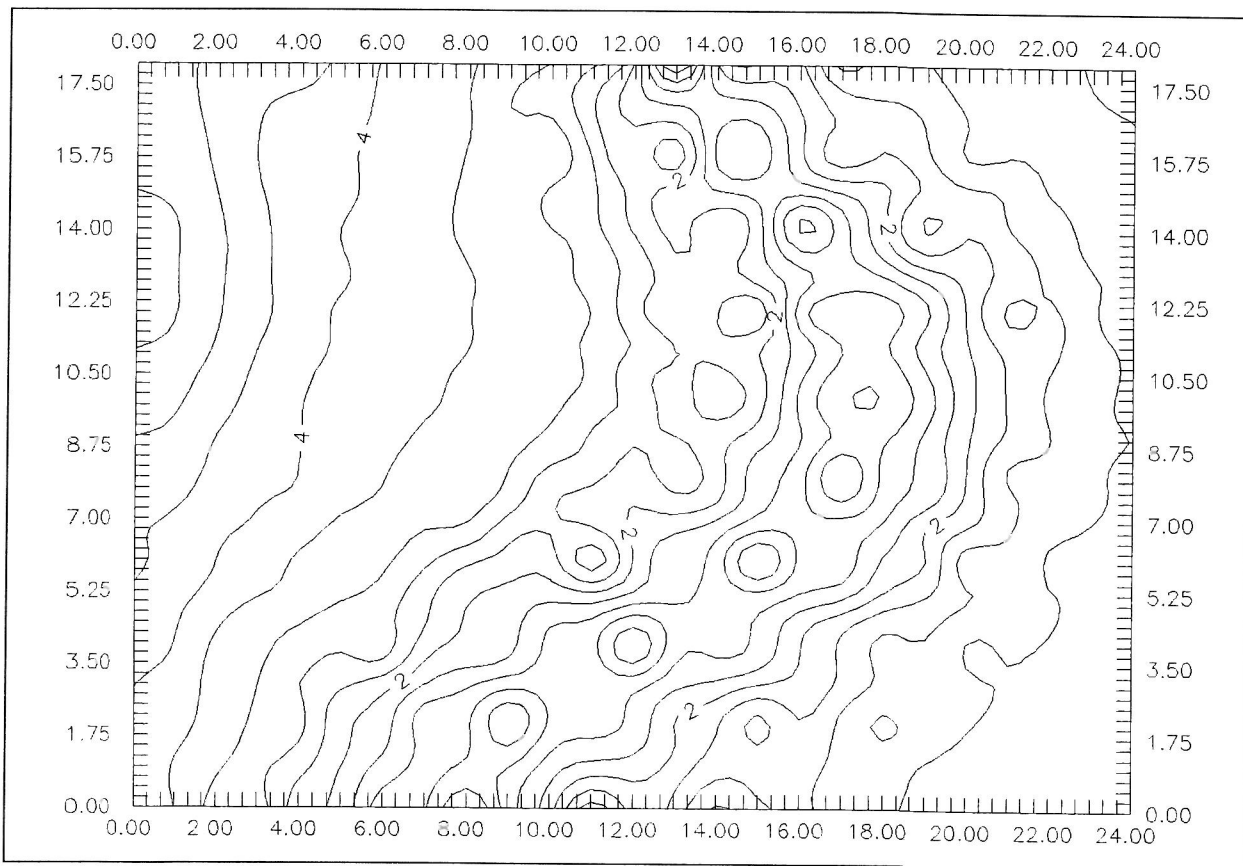


Figure 1.11: 2D contour of an ancient river course extracted from a GPR data set using RAS. The surface was clearly defined in the GPR data but in the common case of general urban strata each bed, most likely, will not be so clearly defined due to inhomogeneity and so this type of processing is generally not applicable.

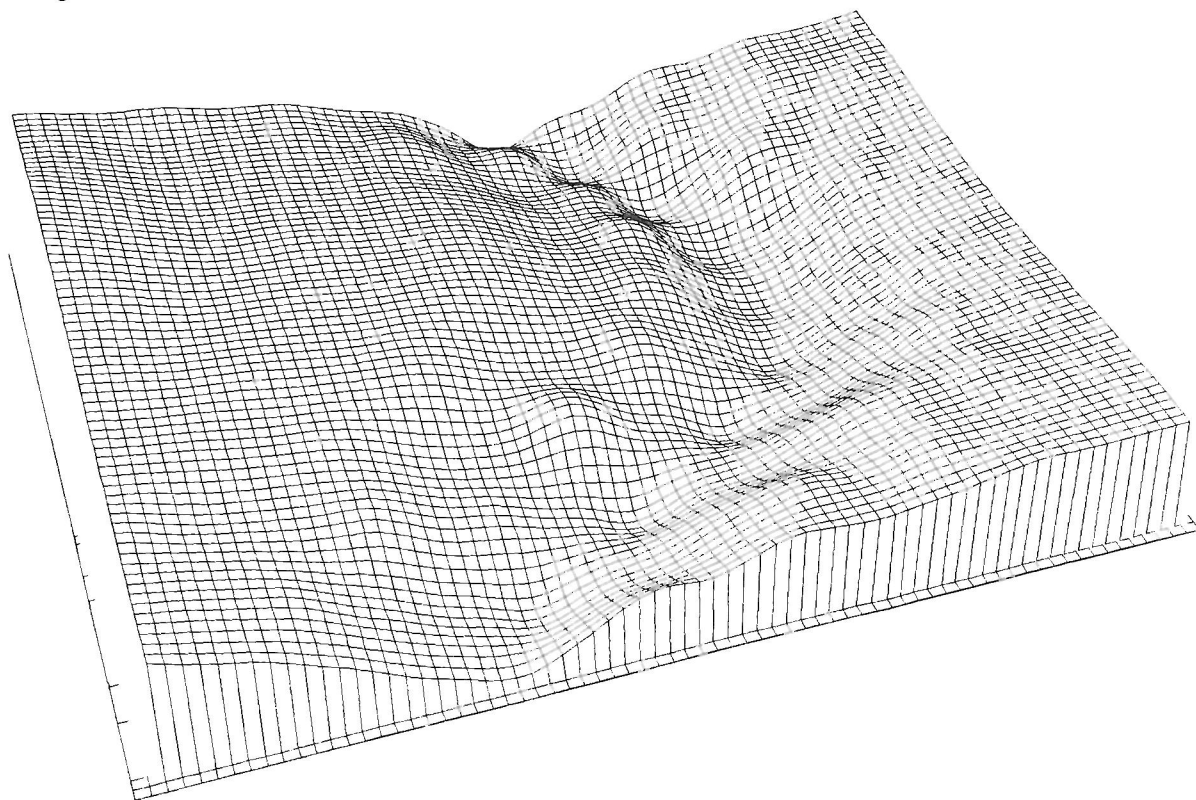
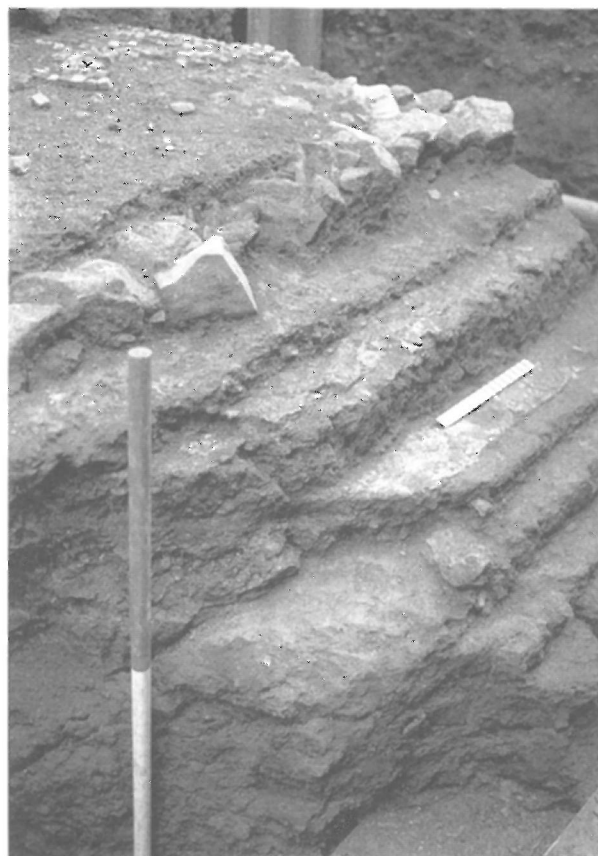


Figure 1.12: 3D contour of an ancient river course extracted from a GPR data set using RAS. The surface was clearly defined in the GPR data but in the common case of general urban strata each bed, most likely, will not be so clearly defined due to inhomogeneity and so this type of processing is generally not applicable.

Figure 1.13: There was over 1m of superimposed floor levels recorded during the Ladybellegate Street excavation. Although of great importance in dividing the site into its stratigraphic horizons and clearly visible to the naked eye, the floor levels had similar electrical properties and therefore were not as clearly defined in the radar traces. Such difficulties have great implications in attempting surface modelling of complex archaeological stratigraphy. (photo: City Archaeology Unit, Gloucester City Council)



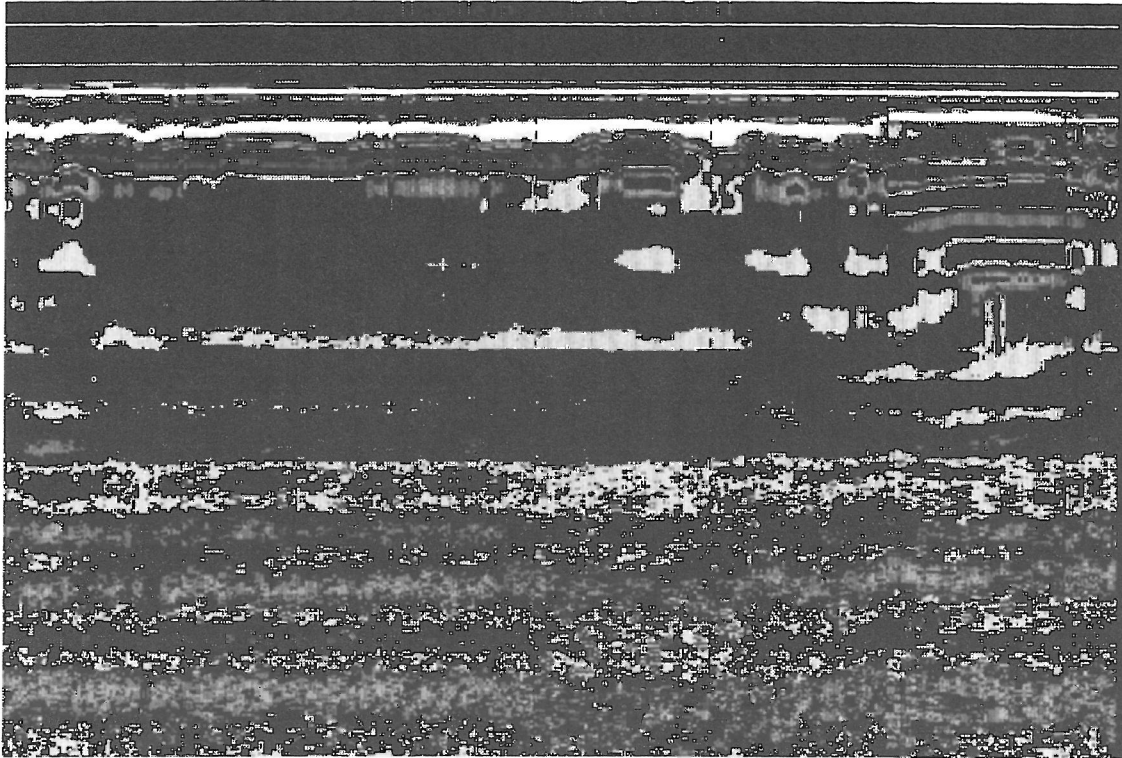


Figure 1.14: Raw data as was collected by the Sir 10 radar systems. The only off-line processing carried out was colour mapping prior to display. Note: this is a B/W representation of a 16 colour display.

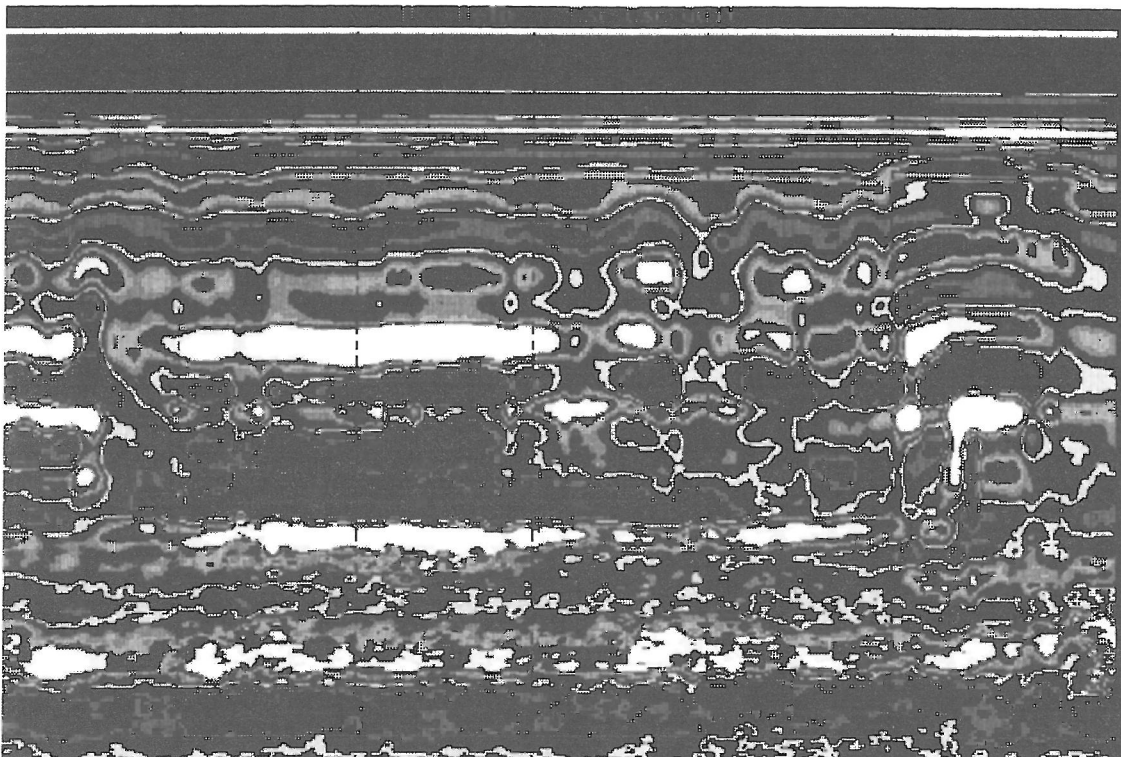


Figure 1.15: Data after processing through the RAS system. Digital processing has been able to enhance small signal variations not obvious in the raw data. Note: this is a B/W representation of a 16 colour display.

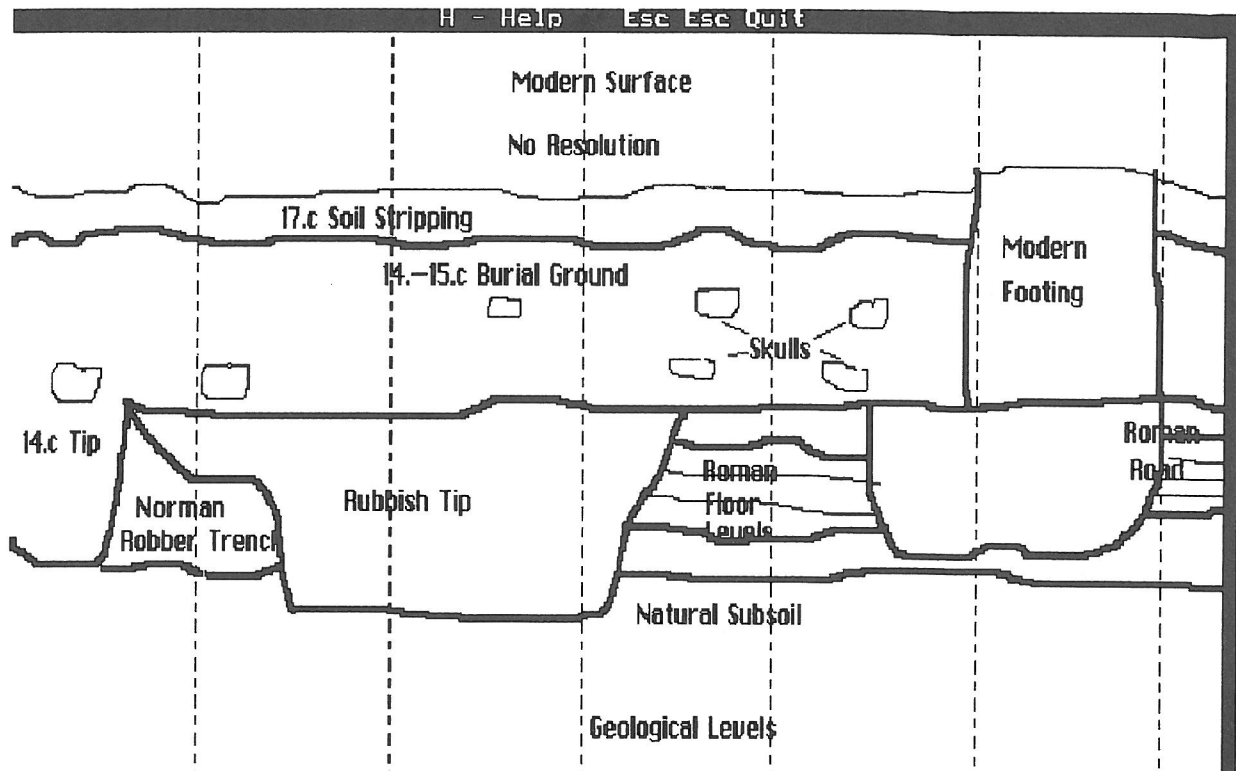


Figure 1.16: Interpretation of the processed data. GPR data has been correlated with a trial trench excavated at the exact location of the transect.

intermediate shortening of the building), whilst the time slices highlighted a series of anomalies visible on the north side which suggested an attached semi-circular feature. This matches the only surviving piece of the Kings Board which now stands as an isolated gazebo (see Figure 1.9). This was probably an open pulpit with a large preaching yard in front. Figures 1.8 and 1.10 show the time slices and plan interpretation respectively.

1.3.2 Surface modelling

Data extracted from both the above interpretation aids can be output in ASCII form for input into CAD or sub-surface modelling. If the stratigraphy is clearly defined in terms of contrasts in electrical properties in the data, individual surfaces can be digitised with a mouse and output to a sub-surface modelling package. Figures 1.11 and 1.12 show 2D and 3D representations of an ancient surface respectively. Two points must be noted when considering mapping surfaces:

- 1) Surfaces of major archaeological significance might not appear in the data e.g. subtle changes in soil colouring might not have an associated change in electrical properties and

therefore will not show up in the radar data (Figure 1.13);

- 2) In an urban environment the subsurface is likely to be very inhomogeneous and features such as pipes and stones will mask the stratigraphic surfaces.

Surface mapping has not been applicable in any of the sites in Gloucester looked at to date, and it is likely that this will be the case in other complex urban sites. Surface mapping is most applicable on green field sites, but here GPR as a geophysical technique might not be the most cost-effective due to the usual large scale nature of the sites. Care must be taken when extracting these surfaces, as the transect data does not represent images of 2D sections as in conventional archaeological investigations. To extract dipping or curved surfaces, the beam characteristics need to be removed from the data using processes such as migration or synthetic aperture processing. To date, algorithms to carry these out on GPR have not been successful due to poor signal/noise ratio of GPR data. If, for example, a curved surface has been chosen, the most reliable way to image the true surface would be to "pick" the surface shown on the radargram and then apply a migra-

tion algorithm to the single point–picked surface data. This overcomes the signal to noise problems. To model these sorts of surfaces in depth and distance without conditioning the data with such processes first would be geophysically invalid and is symptomatic of a grossly simplistic view of interpreting GPR data.

1.3.3 Resolution

Figures 1.14 and 1.15 show raw data and processed data respectively. The data is taken from the Ladybellegate Street site in Gloucester. A 20 m long trial trench was subsequently dug at this location (Figure 1.2) and the interpretation on Figure 1.15 is the correlation between the GPR and excavated evidence. The correlation was very good. Small objects with strong contrasts in dielectric constants turned out to be skulls from the 14th/15th century burial ground of the Blackfriars (Figure 1.17). To date, this represents the maximum resolution of an individual archaeological entity within a GPR survey in the city. Using this correlation of the trench to the GPR, it was possible to extend the GPR interpretation away from the trench into the surrounding 2100 m² of the survey with a good degree of accuracy. The limits of the graveyard and lines of earlier robber trenches and intact walls with intervening street zones were mapped, and the degree of disturbance posed by a 17th century reduction of the site and 19th/20th century cellars was assessed. This survey was carried out on a 2 m grid but further work has suggested that a 1m grid is necessary whenever detailed plan layouts are sought. This is both because of the complexities of interpreting room divisions, and because the character of fills of robber trenches can change dramatically in electrical terms over quite short distances.

The site also contained a good warning as to the dangers of over–enthusiastic interpretation. On Figure 1.15 it is possible to see between chainage 1.5 m to 3.0 m (vertical dashed lines every metre), at a depth one third of the way down the section, a feature which resembles to the eye a buried body with intact head, chest, legs and even the toes turned up (feet at 1.5 m, head at 3 m)! This is, indeed, the exact level at which the graves were found. Without geophysical expertise, it would be simple to make the mistake of interpreting this as a body, but such a feature would not appear as this type of anomaly. No such burial was found at this position in the excavation. It would not be a surprise if such an interpretation from another site were sitting in someone's archives today.



Figure 1.17: A number of anomalies showing in the GPR survey on the Ladybellegate Street Car Park were confirmed as being signals emanating from human skulls. To date, these have been the smallest individual archaeological artifact that have been isolated in a GPR survey carried out within Gloucester. Graves as such were not visible in the survey (although the possible outline of more substantial brick-lined burial vaults were recorded in the Westgate Street survey). (photo: City Archaeology Unit, Gloucester City Council)

GPR Evaluation Timetable

- G: Collect digital GPR data over a reasonably–sized area.
- G: Process GPR data: light filter + horizontal rectification.
- G&A: Interpret data on a macro scale to position trial trench(es).
- A: Trench excavation.
- A: Interpret excavation.
- G: Calibrate and classify GPR data using trial trench evaluation.
- G: Optionally reprocess data to enhance features of interest.
- G&A: Reinterpret data using trench classification — interpret data gradually moving away from the trench.
- G&A: GPR report.
- G&A: Integrate GPR results with Archaeological results — CAD.
- A: Archive GPR data to allow detailed reprocessing and interpretation during future development planning.

Figure 1.18: Ground Probing Radar Evaluation Time Table showing the degree of cooperation required between geophysicists (G) and archaeologists (A).

1.4 CONCLUSION

Ground Probing Radar is now in a position to make a significant contribution towards archaeological evaluations, but it must be used correctly. It must also be appreciated that it is not a quick and simple solution to the interpretation of a site.

Adequate time and resources must be built into a project that intends to use it. From experience in Gloucester, it has been possible to define a GPR evaluation time table (Figure 1.18). This can be structured to produce different levels of information as appropriate to the immediate task in hand, but also with the provision to return later to the data and carry out more detailed or extensive analysis. The data does in effect become an active part of the Sites and Monuments Record. The flow chart also illustrates that the key to a proper evaluation of the GPR data is a close, and long-term co-operation between the geophysicist and archaeologist.

The development of the software tends to be never-ending as new projects highlight fresh problems to solve. Current developments with significance to Gloucester archaeology include target recognition and time slice averaging to enhance dipping and curved features.

When appropriate within a project structure for a particular site, the GPR technique has become an important tool for archaeological investigations in the city of Gloucester, and shows great promise on many other urban sites. But the interpretations outlined in this paper have only been made possible by developing a software package tailored to this particular type of investigation. A traditional GPR survey would possibly only have yielded information to the fact that the sub-surface was inhomogeneous and a plan with hundreds of anomalies marked. The archaeologists would have been able to predict that degree of complexity without the expense of a GPR survey! If GPR continues to develop its potential then it will play an increasingly important role as developers demand clear evidence for recommendations being made by archaeologists to planning authorities. But the technique must be handled correctly. It is quite possible that some of the archaeological surveys will end up as evidence in Public Enquiries. It does neither archaeology, nor

GPR itself, any good if over enthusiastic interpretations — based on a poor understanding of the basic principles of the technique — are able to be discredited in such a forum by geophysicists or scientists from an opposing point of view. The value of GPR is as an objective instrument. We must be precise about what is actually being recorded — and then the methodology by which the interpretation are made.

Acknowledgements

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